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# **A PLAN FOR DEVELOPING A HIERARCHAL THREE-DIMENSIONAL LANDSCAPE SIGNATURE MODEL**

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## PREFACE

The study reported herein was developed by personnel of the U.S. Army Engineer Waterways Experiment Station (WES) from March 1991 to December 1991. The study was funded by Headquarters, U.S. Army Corps of Engineers, under Department of the Army Project No. AT22-SC-001, Task QG, Work Unit E01, "Scene Dynamics."

The study was conducted under the general supervision of Dr. John Harrison and Dr. John W. Keeley, Director and Assistant Director, respectively, of the Environmental Laboratory (EL), WES, and Dr. Victor Barber, Acting Chief, Environmental Systems Division, EL, and under the direct supervision of Mr. Ken Hall, Acting Chief, Environmental Constraints Group (ECG), EL.

This report was prepared by Mr. Randy Scoggins, ECG, EL, and Dr. Lee K. Balick, EG&G Energy Measurements Inc., Las Vegas, NV.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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# CONTENTS

	<u>Page</u>
PREFACE . . . . .	1
PART I: INTRODUCTION . . . . .	3
Background . . . . .	3
Scope . . . . .	4
PART II: CONCEPTUAL DESIGN OF THREE-DIMENSIONAL LANDSCAPE SIGNATURE MODEL . . . . .	7
Objectives . . . . .	7
Conceptual Design . . . . .	7
Physical Processes to Model . . . . .	8
Computational Approach . . . . .	10
PART III: RESEARCH AND DEVELOPMENT TECHNICAL TASKS . . . . .	14
Information Base Design and Development . . . . .	14
Preprocessor Environmental Models . . . . .	16
Temperature Models for Landscapes and Component Objects . . . . .	17
Illumination and Scattering Models for Active Systems . . . . .	20
Directional Radiance Model . . . . .	20
Scene Projection Process . . . . .	21
Validation, System-Level Integration, and Sensitivity Analysis . . . . .	22
PART IV: SUMMARY . . . . .	23
REFERENCES . . . . .	24
TABLE 1	

A PLAN FOR DEVELOPING A HIERARCHAL  
THREE-DIMENSIONAL LANDSCAPE SIGNATURE MODEL

PART I: INTRODUCTION

Background

1. U.S. Army laboratories have been leaders in developing and utilizing numerical models to simulate terrain electromagnetic background signatures and their variability. The U.S. Army Engineer Waterways Experiment Station (WES) Environmental Laboratory (EL) has developed models for simulating the environmental effects on thermal infrared (IR) backgrounds and provided leadership in database development to drive these models. The U.S. Army Engineer Cold Regions Research and Engineering Laboratory has provided leadership in program development for complex scene modeling, as exemplified by the Tri-Service Smart Weapons Operability Enhancement (SWOE) Program, and in model development. The U.S. Army's Atmospheric Sciences Laboratory has contributed in the area of atmospheric electromagnetic energy modeling. The U.S. Army Engineer Topographic Engineering Center (TEC) has made contributions in the area of computer image generation. The Keweenaw Research Center has developed thermal models, most notably for vegetation foliage. The recent SWOE Program demonstrations have drawn on the expertise of these and other organizations to begin the development of a capability for multispectral simulation of complex three-dimensional scenes. The direction for future research and development described in this paper relies heavily on the experience and capabilities of these organizations and laboratories.

2. One-dimensional terrain surface temperature models developed at WES (Balick et al. 1981) have been used to simulate dynamic environmental influences on thermal IR background signatures for over 10 years. An early use at WES was for the evaluation of thermal IR camouflage effectiveness for fixed installations. More recently, these models have been applied to work ranging from sensor/weapon tactical decision aids to generating input for effectiveness assessment of developmental and conceptual advanced smart weapons designs.

3. Most of the existing models assume horizontal homogeneity of the surface materials and of their environment. They cannot easily incorporate the complex three-dimensional energy fluxes in landscapes with significant

topography or in the vicinity of objects. Additionally, since they are point models, they use weather data collected from only one nearby weather station. This means that no spatial variation of the atmospheric environment such as that because of topography or surface cover can be considered. Temperature predictions for large areas can thus not include effects that are intrinsically two-dimensional or three-dimensional. Also, capability to predict future weather conditions is not available in the models.

4. Recent applications have extended the one-dimensional (point) model to two dimensions by applying the model using data sets containing large-scale maps of surface material types, slope, etc. (Kress in preparation). By using simple adjustments for surface slope in areas with terrain relief, these data have extended the models to enable quasi-three-dimensional representations of surface temperature or radiance. However, the assumptions and limitations of the one-dimensional temperature models still remained. Accurate simulations of the energy fluxes in complex geometric landscapes with spatially and temporally varying atmospheric environment are still necessary for generation of realistic three-dimensional scenes.

#### Scope

5. The approach to landscape scene simulation proposed applies to the simulation of scenes for active and passive sensors operating in the ultraviolet through the millimeter wave (MMW) spectral regions. Specific attention is given to passive visible/near-infrared (V/NIR), passive thermal scenes, and active MMW radar. However, because of its inherent temporal and spatial complexity, research is strongly focused on thermal IR scene simulation. Extensions are presented for passive V/NIR and active MMW scene simulations.

6. Accurate three-dimensional thermal modeling of landscapes has proven to be an immensely complex task. To cope with this complexity, this plan relies heavily on multiscale and multiresolution concepts. To avoid confusion, the term "scale" refers to the spatial and temporal levels over which relevant physical processes take place, and "resolution" refers to the spatial and temporal detail at which these physical processes are simulated by the models. The term "scene" as used here refers to the three-dimensional landscape signature information produced by the physical models and not to the two-dimensional perspective projection of the scene information onto the sensor input plane. "Scene projection" refers to the overall process which

projects the emitted radiance determined from the full set of scene information, i.e., geometry, surface temperatures, etc., onto the two-dimensional array at the sensor input plane. Carrying this radiance array through a sensor simulation will result in the final image. The intent of the multilevel approach is to compute only what is necessary for a desired application sensor, as illustrated in Figure 1. In addition, the plan relies on recent developments in computer graphics, hardware, and the computational techniques for the simulation of radiant energy transfers within the landscape to generate the scene.

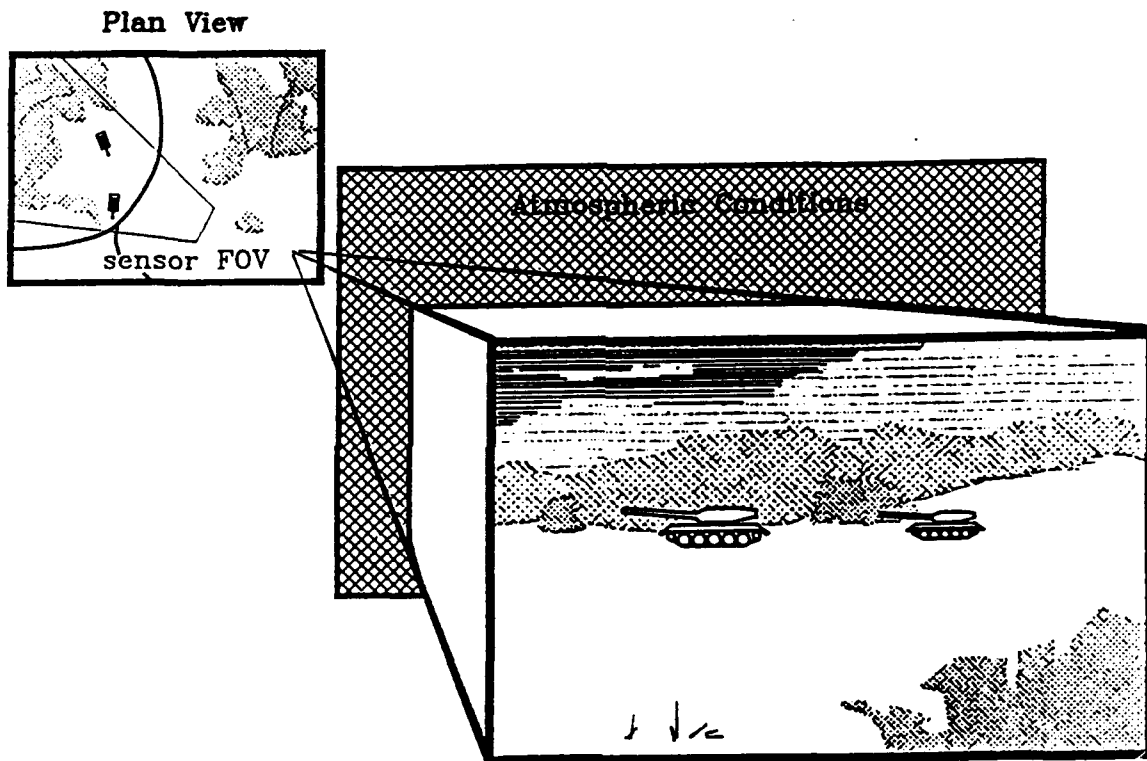


Figure 1. Area of temperature prediction

7. Future requirements for scene simulation will require models of improved fidelity that take into account complex, interacting scene geometries and environmental processes. This paper presents a path to a practical three-dimensional modeling capability that encompasses all the major phenomena which come together to produce scenes of complex landscapes. A combination of algorithm advances in such diverse areas as numerical meteorological modeling and computer graphics, as well as advances in computer power, makes a practical three-dimensional model possible. Some of the components already exist



as code and will require straightforward modifications and module integration. Other components are still theoretical and must be researched for optimal implementation and realization.

8. Although the authors initiated the preparation of this plan, crucial concepts were developed during a workshop held at WES in early 1991. Major contributions to this plan were made by the following participants (in alphabetical order): Dr. Christoph Borel (Los Alamos National Laboratory), Dr. James Dorband (National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC)), Dr. James Kajiya (California Institute of Technology), Dr. Holly Rushmeier (Georgia Institute of Technology), Dr. Peter Shirley (Indiana University), Dr. James Smith (NASA/GSFC), and Dr. Angelo Yfantis (University of Nevada at Las Vegas). Workshop participants also provided valuable reviews of preliminary drafts of this report to the authors.

## PART II: CONCEPTUAL DESIGN OF THREE-DIMENSIONAL LANDSCAPE SIGNATURE MODEL

### Objectives

9. The purpose of the work described in this plan is to develop models to enable the calculation of realistic computer-generated images of terrain and objects in or on the terrain landscape. These images will represent specific sensor views within a larger landscape area on the order of a few square kilometers. The basic assumption here is that the sensor will view a relatively small portion of the overall landscape database at high resolution. The modeling system should be capable of generating a scene description with resolution at 1 m or less. The general approach is appropriate for active and passive sensors at most spectral regions of interest, i.e., 8 to 12  $\mu\text{m}$  for thermal IR and MMW radar, given appropriate surface emittance, reflectance, and polarization characteristics. The focus of the plan, however, is on thermal IR because its strong dependence on the environment and its time-dependent nature make it the most intricate problem. Extensions to active systems, varying sensor viewing geometries, and other spectral domains are discussed. A broad overview of the approach is presented with the expectation that some technical issues addressed with specific tasks will be refined as work progresses.

### Conceptual Design

10. Multiple level approaches are taken both to incorporate physical processes in the model and in the computational techniques used. Energy budgets will be evaluated for the thermal simulations at two main levels of resolution: a low-resolution model and a high-resolution model. Each level contains simulations of energy fluxes at the desired scale with appropriate computational methods accurate to the desired resolution. Low-resolution modeling provides the temporal history and spatial environment for the high-resolution model. The high-resolution model simulates a subarea within the low-resolution simulation but includes much more spatial detail, modeled for a shorter time history. Additionally, a number of other tasks are required to provide input data, simulate atmospheric effects, and perform the scene projection. This section briefly presents the structure of the multi-level

system. First, the individual energy budget components are described including comments on the ways phenomena operating at different scales are modeled. Then the general computational approaches recommended to simulate these processes at the desired resolutions are presented. Finally, the directions for extension to simulation at shorter wavelengths and to active systems are noted.

11. The fact that an overall systems approach is required and that the approach should be kept as modular as possible should be assumed. An end-to-end capability needs to be developed quickly, even though it will be primitive initially to allow for comparisons of alternatives and to determine resource priorities. Some of the recommendations made are conceptual to some degree since they draw upon ongoing basic research in the area and are subject to modification as work progresses and optimal implementation-specific details are selected.

#### Physical Processes to Model

12. The task of computing temperatures of many surfaces of varying materials is largely one of determining the energy budget of the surfaces over time. The energy budget can be viewed as a balancing of three major categories of energy fluxes: radiant, turbulent, and conductive. (This breakdown is somewhat an oversimplification made for the purposes of a clear discussion.) For landscape simulations, each of these fluxes acts at varying degrees on more than one spatial scale, so scale-specific calculations are used. To the extent that meteorological classifications are appropriate, atmospheric environmental variation is treated at the mesoscale; landscape radiant interactions are both mesoscale and microscale; and the individual surface energy budgets are evaluated at the microscale. The general approach to each of these categories is discussed below.

#### Radiant energy fluxes

13. Radiant energy flux takes place at solar (V/NIR) and thermal IR wavelengths and, in a three-dimensional (3-D) landscape, allows surfaces to interact with each other to varying degrees depending on the distance between them, relative orientation, and other factors. In the V/NIR or "shortwave," the primary source of energy is the sun with strong modulation by the atmosphere. The atmosphere is 3-D at landscape scales. Clouds and objects on the ground not only cast shadows but reflect light; they are secondary sources of

shortwave energy with strong spatial variation. Therefore, there are two major components to modeling global shortwave energy in three dimensions: modeling the sky irradiance field and modeling the redistribution of light by objects and landscape topography. Thermal or "longwave" energy is emitted by the atmosphere and by all surfaces. The distribution of longwave energy from the sky is relatively even spatially and temporally and is generally of secondary importance for local scene contrast. However, atmospheric thermal radiation is a major component of the overall landscape surface energy budget and must be accurately modeled if absolute temperature predictions are to be correct. Three-dimensional landscape and object surfaces interact with each other over distances through thermal IR emission and absorption. The subsequent redistribution of energy in this manner can be strong and is a significant source of local scene contrast, especially at night.

14. The simulation of shortwave and longwave atmospheric fluxes should be based on atmospheric radiation and propagation models. A mesoscale meteorologic model can be used to describe a 3-D atmosphere over the landscape, including a statistical description of clouds and computation of radiation upwelling from the landscape surface to the atmosphere (spatial detail is not needed for this). Specific cloud geometries could be specified in the model if needed. Shortwave and longwave interactions between landscape surfaces can be well modeled using radiosity and ray-tracing procedures.

#### Turbulent energy fluxes

15. Turbulent fluxes involve transport of sensible and latent heat by mass movement or turbulent eddies. Turbulence generates interaction between surfaces and the atmosphere, but not usually strong interaction between different surfaces. Surface temperature models use micrometeorologic parameterizations of turbulent fluxes; they use surface and atmospheric boundary layer (weather station) properties for inputs. Because of the way these parameterizations usually are applied, the atmosphere is not modified by these interactions, and the boundary layer is usually assumed constant over the landscape. Both usages are significantly incorrect at landscape scales. The spatial variation of the atmosphere is generally smaller than other energy budget terms and can be simulated with a mesoscale meteorologic model.

16. The current microscale parameterizations assume a nearly horizontal slope. This is obviously inappropriate for 3-D objects and steeply sloped landscapes. The solution, especially for objects, appears to require an approach through computational fluid dynamics (CFD). The computational

magnitude of this technique presents problems as compared with the degree and nature of the errors introduced in the resulting scene by less rigorous approximations. Since these are not well understood, application of CFD will be limited and not be made part of the near-term goals of the plan. Perhaps a satisfactory solution and implementation of this type of calculation will become available as work progresses. Also, excluding some local aerodynamic effects, turbulent fluxes generally have less effective spatial variability than the radiant energy transfer processes.

#### Conductive energy flux

17. Heat conduction and storage occur within the solid materials in a landscape. This process embodies the time history dependence of temperatures and is a significant reason for the numerical complexity of numerical scene simulations. Some terrain types, such as forests, are composed of multiple material types and/or complicated geometric arrangements. Differences of heat conduction in materials are the principal reason for local contrast in thermal scenes, especially at night. (Mass transports of heat within porous materials can be significant. For this discussion, they are lumped temporarily with conductive fluxes; all fluxes within the materials are called conductive.) For most terrestrial materials, differences between material conductive properties create larger temperature effects than conduction between surfaces or materials. Additionally, 3-D models are time-consuming to operate and execute. Therefore, it is recommended that great reliance be placed on one-dimensional conduction models until specific needs for 3-D models are identified and developed.

#### Computational Approach

18. The computational approach is implemented in phases and is strongly multiresolution oriented. There are six major computational phases: (1) information base design for geometry and material attributes, (2) preprocessor atmospheric environmental model including mesoscale meteorological modeling, (3) two-step, low-to-high spatial resolution landscape temperature modeling with decreasing field-of-view, including component object temperature models, (4) illumination and scattering models for active systems, (5) directional radiant exitance modeling, and (6) the final scene projection process. These phases and their relationship to each other are illustrated in a block diagram in Figure 2. Information base generation will essentially be a one-time step

Specific to Geographic Location and general weather condition. Generally a one-time setup process.

Specific to sensor field of view and time of day. Rerun when these conditions change.

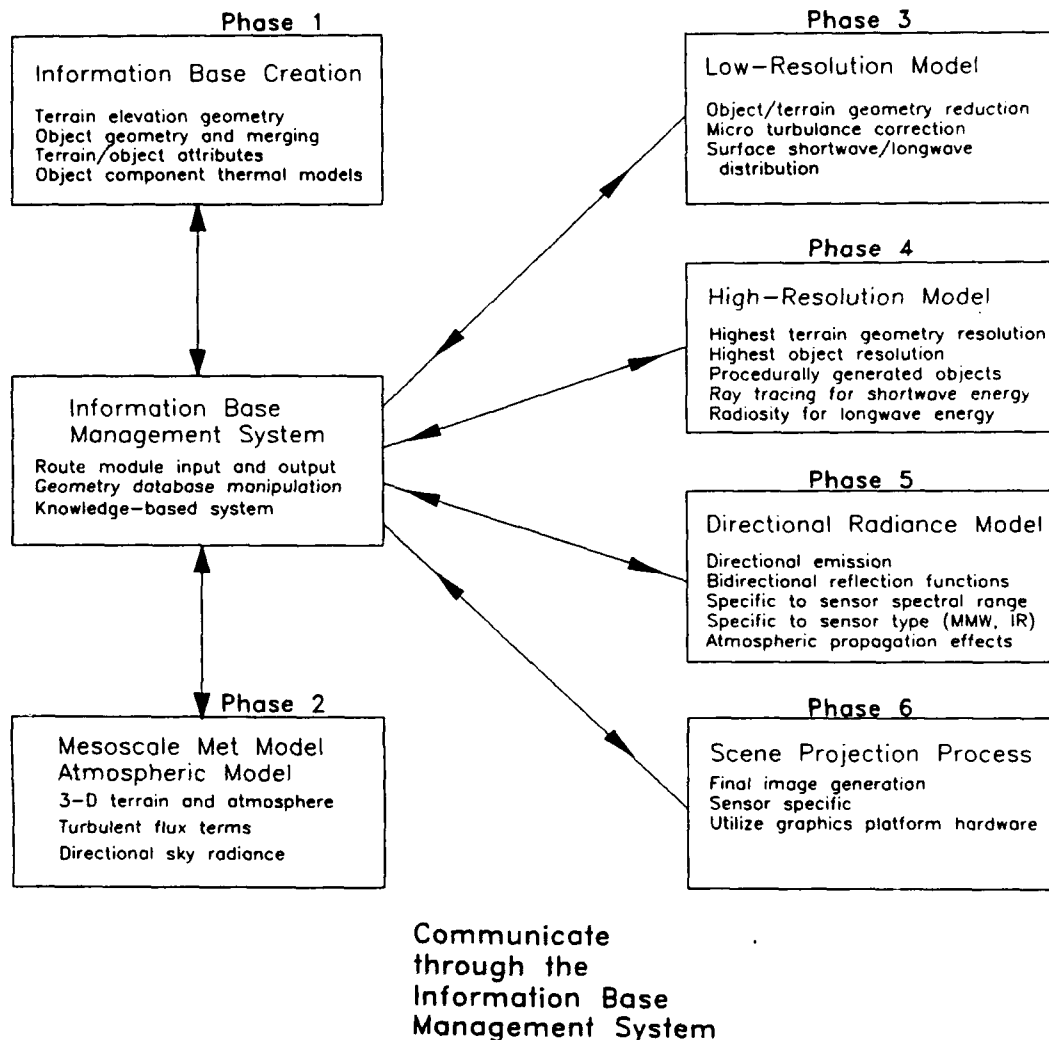


Figure 2. Relationship of phases in landscape signature model

for a given geographic region, although updates will be required as objects such as vehicles are placed in the scene. This is a very important phase since it will be used by all succeeding steps of the process. The atmospheric environmental models will be implemented as a preprocessor to initialize the energy budget for the entire landscape with the mesoscale meteorological model (MMM). The energy budget will then be evaluated, utilizing weather conditions prestored from the MMM, through a "spin-up" period before and up to the time-of-interest at low spatial resolution. This step is intended to derive a

thermal time history for the landscape. Using the results of the low-resolution model, the high-spatial-resolution model will then be initialized to the thermal conditions present a short time before the time of interest and will be run only for the area to be viewed by the sensor up to that time. This approach keeps the amount of computations for the nonimaged landscape area smaller while concentrating the greatest computational intensity in the area that will ultimately be viewed. Additionally, surfaces within the high-resolution area can receive radiant energy from surfaces outside this area using the low-resolution model results. High-resolution surface temperatures are then converted to spectral, directional radiance in the scene projection phase producing the final "image." Only a specified subregion of the landscape at a specific time is projected to an image. If multiple terrain areas, view geometries, or times are desired, the high-resolution models of phase 4 and phases 5-6 are repeated.

19. The MMM and the 3-D atmospheric model will be a preprocessor with their outputs entered into the information base. Both interact with the surface, but the interactions are important at spatial scales low enough to be handled at a mesoscale resolution (on the order of 0.5 to 1 km). The low-resolution model is based on the premise that many details and small surfaces in the larger region contribute little to the overall energy budget of the landscape and is designed to avoid computing unnecessary detail at places and times where it is not needed. The high-resolution model provides spatial detail when and where it is needed. The low- and high-resolution models are driven by separate geometric databases, which may be derived from a master high-resolution database with appropriate detail reduction algorithms. Both evaluate energy budgets and use numerical models to calculate temperatures. The evaluation of the radiant fluxes for each resolution uses different combinations of radiosity and ray-tracing techniques optimized for efficiency and the fidelity required for the desired resolution. Turbulent and conductive transfer calculations are dependent on the specific material model used but are similar at either resolution.

20. Three-dimensional treatments of heat conduction would be included in the high-resolution phase where necessary. Resulting temperatures must then be converted to radiant exitance in the direction of the sensor spectrally or integrated over the sensor response band using information on directional and emittance properties. Information on the directional aspects potentially will be obtained from the material temperature models. Finally,

the scene information is projected onto a perfect (no sensor degradation) image plane using workstation graphics hardware and software capabilities. Systems which form their images with different geometries (charge coupled device forward looking infrared versus line scanners, for example) or non-imaging sensors will need different simulation algorithms. Hooks to allow inclusion of future sensor geometries and different output devices into the system will be needed.

21. Scene projections for passive sensors operating in the visible and near-infrared will be simulated using the shortwave irradiance part of the 3-D atmospheric radiant transfer model and the high-resolution geometry from the thermal simulations. Directional, spectral reflectance functions need to be supplied. The projection will then be modeled using ray tracing and radiosity in a fashion now well developed in computer graphics. Scene projections for active sensors such as radar can be modeled in a similar way, except illumination source information and appropriate reflection functions must be specified. Some difficulty may be encountered in specifying directional scattering functions and in dealing with interference effects and other effects peculiar to certain systems.



### PART III: RESEARCH AND DEVELOPMENT TECHNICAL TASKS

22. A considerable amount of research and development (R&D) is needed to implement the hierarchical model both in the physical process simulation and in the computational techniques. The basic approach has been examined in some detail, and it is expected that all problems are resolvable given reasonable attention and time. Nevertheless, the development and integration requirements are numerous. Primary components and specific R&D tasks are summarized as follows:

- a. Information base design and development.
  - (1) Surface properties.
  - (2) Mass properties.
  - (3) Spatial resolution requirements.
  - (4) Interfacing model phases.
- b. Preprocessor environmental models.
  - (1) Mesoscale meteorological model.
  - (2) 3-D atmospheric radiant transfer model.
  - (3) Cloud and obscurant models.
- c. Temperature models for landscapes and component objects.
  - (1) Scene-component thermal conduction models.
  - (2) Low-spatial-resolution temperature model.
  - (3) High-spatial-resolution temperature model.
  - (4) Turbulent flux at varying spatial detail.
- d. Illumination and scattering models for active systems.
- e. Directional radiance model.
  - (1) Temperature to radiance conversion.
  - (2) Texture simulation.
- f. Scene projection process.
  - (1) Procedure and techniques.
  - (2) Atmospheric effects on final sensor-plane radiance.
- g. Validation, system-level integration, and sensitivity analysis.

#### Information Base Design and Development

##### Surface properties

23. The nature of thermal modeling suggests representing objects and landscapes as 3-D masses bounded by two-dimensional surfaces. Bounding

surfaces must be geometrically defined, most likely as a set of polygons and parameters used by the surface energy budget associated through some data structure (Kress 1991). The evaluation and selection of data structures requires early R&D efforts. Polygonal descriptions of the landscape are most appropriate for graphics workstations and for radiosity-based surface longwave radiant energy exchange. However, techniques which take into account the regular grids that define landscape surfaces with elevation data will be the most efficient. Polygonal geometry creates difficulties elsewhere, as in forest canopy representation, and alternatives such as procedurally generated surfaces will be considered for some of the modeling functions. Any geometry database must be supported by a software system which includes polygon mesh generation, capabilities to convert between object representation schemes, geometric merging, Boolean operations, spatial scale transformation, and dynamic mesh refinement.

#### Mass properties

24. Solid geometry representation of 3-D objects is necessary for the thermal conduction calculation. Properties such as thermal conductance and diffusivity must be specified on regular 3-D grids for numerical solution of the diffusion equations in solid objects. In many cases, one-dimensional thermal conduction calculations will be adequate for landscape modeling. However, for full detail, 3-D representation of the mass properties of objects and some landscape components will be required to achieve the highest accuracy. Mass properties of 3-D solids will most likely be stored in a volume-element or voxel form, possibly using an octree structure.

#### Spatial resolution requirements

25. Hierarchical database techniques are necessary since each modeling phase will require data for use at different spatial resolutions. Elements need to be merged and/or a method found to determine overall bounding volumes with effective internal mass properties. The mechanics for doing this will be identified and developed. Hopefully, this process can become highly computer assisted. In the ideal case, merging will be done automatically based on the relation of individual landscape element size to the desired final scene resolution. Lumping or aggregating landscape components will not be a trivial task, and testing sensitivities and alternatives will require careful development.

### Interfacing model phases

26. An efficient scheme is required to attach model attributes (conductivity, emissivity, etc.) to the landscape and object geometry representations. Again, the multilevel nature of the approach will require techniques for combining attributes in some meaningful manner where spatial reduction is performed, but care must be taken in averaging and weighing different material components. Also, since the database will serve all phases of the modeling system, efficient means of linking each phase to the database for storage of output and retrieval of input are required.

### Preprocessor Environmental Models

#### Mesoscale meteorological model

27. The MMM recommended for implementation is the High Order Turbulence Model for Air Circulation (HOTMAC) (Yamada 1978). HOTMAC is a comprehensive physically based 3-D atmospheric model. Research is needed to link it spatially through the database with the temperature simulation models in a physically correct way. Predictions of surface temperature from the MMM will be used to initialize the low-resolution thermal model. Also, turbulent fluxes from the MMM will be used and possibly refined for the subsequent surface energy budget calculations. The spatial resolution at which the MMM operates is significantly rougher than the low-resolution thermal model. Techniques to transfer the information from the resolution of the MMM to that of the remaining thermal models will be developed. Simple interpolation is not appropriate for this application. Model sensitivities need to be examined for optimal performance for this application. This model will also yield two important capabilities: extrapolation of weather station data to the study area (with limits), and a temporal predictive capability for surface weather over the landscape (assuming steady-state synoptic conditions). The uses, limits, and assumptions of these will be explored. Output will be linked with the 3-D atmospheric radiant transfer model via the information base.

#### 3-D atmospheric radiant transfer model

28. A model to calculate the spatial distribution of longwave radiance emitted from the atmosphere is necessary for a 3-D surface energy budget. This model will also calculate solar radiance and account for atmospheric attenuation. The 3-D atmospheric model will be conceptualized and developed. Most of the technology exists, depending on what the model is expected to do;

that is, the radiant transfer through most atmospheres can be well modeled, but certain problems, such as clouds, require additional research. Linkages through the database to the MMM and the surface temperature modeling system will be developed.

#### Cloud and obscurant models

29. A companion model to HOTMAC, the Random Puff Transport And Diffusion model, simulates 3-D dispersion of gasses and aerosols and may be useful for modeling obscurants at the mesoscale. A suitable model to account for the reflection and attenuation effects of cloud cover is also desirable. Where possible, existing work appropriate to cloud modeling will be identified and utilized. Experiments using the MMM to estimate cloud cover factors will be performed.

#### Temperature Models for Landscapes and Component Objects

##### Scene-component thermal conduction models

30. Component objects considered here are objects that are located on or partially in the landscape surface, such as boulders, roads, and buildings. Satisfactory temperature models do not exist for all surfaces and objects present in the 3-D landscape. Of particular interest are forest edges, isolated trees, and many 3-D objects. This is a major problem affecting the range of simulations which can be technically correct. Priority effort will be given to temperature numerical model development. There may be some cases in which knowledgeable estimates are useful where numerical models are unavailable. An example would be for sea ice. These cases need to be identified and the knowledge incorporated into the system, possibly using knowledge base system concepts. Where little knowledge exists, some way to enter expert knowledge interactively should be included.

31. 3-D heat conduction models will be needed for component objects. Because of their developmental nature, the relatively high degree of expertise, effort and manpower to use them, and their run times, they should be used only when necessary. Specific needs will be identified as the program progresses, but generic procedures for incorporating them in the system need to be initiated early. Acquisition of generic conduction models such as TOPAZ (Shapiro 1986) from Lawrence Livermore Laboratory is recommended. The surface energy budgets necessary to drive the conduction models will utilize turbulent fluxes from the MMM, possibly modified for increased spatial detail, and

radiant flux calculation using a combination of physically based radiosity and ray-tracing techniques.

#### Low-spatial-resolution temperature model

32. The low-resolution model provides the temporal background and spatial energy flux environment for the high-resolution simulation. Simulations will cover an area on the order of tens of square kilometers and for as much time history as needed--on the order of tens of hours. Temporally, it will provide initial conditions for the high-resolution simulation. Spatially, it will provide the energy flux environment within which the high-resolution simulation will be made. The practical objective of the low-resolution model is to avoid the computation of unnecessary detail while still providing a physically based simulation of the environment and energy fluxes within a landscape. The high-resolution modeling will operate within the area of the low-resolution simulation over a shorter time.

33. The low-resolution model will describe the energy flux environment of the high-resolution area by several techniques. Radiant fluxes between the sky and terrain will be derived by an atmospheric radiance submodel. Surface-to-surface radiant energy exchanges will be simulated using temporally and spatially varying wind, air temperature, and humidity estimates from the MMM. Heat conduction simulation will probably be restricted to one dimension (but in an overall 3-D environment) in the low-resolution model. Higher dimensionality can be included if it is shown to be warranted. While the low-resolution model is not expected to have a strong impact on local thermal contrasts within the final scene, it is crucial to simulating the global level of energy fluxes and temperatures within the scene and for maintaining integrity in simulating the environmental effects on the scene projection. It is pertinent to the simulation of the scenes for passive sensors in general, but has little or no role in simulations for active systems.

34. Two critical design questions exist. First, what is the greatest level of detail needed in the low-resolution model? When less detail is used, fewer calculations are needed, but also a greater difference has to be interpolated between the low- and high-resolution models. The second issue is the interpolation of information from the low- to the high-resolution model. The low-resolution model cannot contain all the information needed for the high-resolution simulation. For example, with regard to initializing the high-resolution model, the low-resolution model does not incorporate many of the detailed features that exist in the high-resolution model; therefore, it

produces no direct estimates for the initial conditions of these features. Methods to infer initial conditions from the low-resolution model are needed.

High-spatial-resolution temperature model

35. The high-resolution model provides the basis for the final image and contains the necessary detail to simulate important components of local scene contrast. The size of the simulation is anticipated to be on the order of a few hundred meters, with detail on the order of meters, and for time periods on the order of an hour. The geometric description is fully 3-D, and detailed treatments of the energy fluxes within the 3-D space are needed. Radiant energy flux distributions are treated in great detail using radiosity and/or ray-tracing techniques derived from computer graphics. Turbulent fluxes will use atmospheric variables estimated by the MMM which, at least initially, are assumed spatially constant over the high-resolution simulation area. Heat conduction is treated one-dimensionally to the extent possible. However, one-dimensional conduction models are not anticipated to be satisfactory for all situations. The 3-D conduction models are computationally time-consuming and are often specialized. Effort will be expended to determine what is needed, to adapt or develop them, and to determine how these models can best be integrated into the simulation procedures.

36. Optimized ray-tracing procedures will be applied to uniformly distributed points on the polygons defining object surface to calculate net irradiance on the objects. Software such as the RADIANCE package (Ward 1988) developed at Lawrence Berkeley Laboratory can be used to estimate the irradiance given a point in space and orientation by integrating the incoming radiance over all space using Monte Carlo techniques. The irradiance at the sample points will be used in the energy budget at numerical grid points to provide boundary conditions for the 3-D conduction calculations. This same technique may be applied to calculate longwave radiant energy exchange, although radiosity may prove more efficient for this diffuse reflection simulation. Point sampling will also be useful to define shadow areas since the surface can be recursively subdivided until some lower limit is reached, if the variance on a given polygonal surface is too great. Radiant interactions between large areas of the landscape outside of the high-resolution area will be defined and included, probably through a radiosity type calculation.

37. Several issues must be resolved early in the development of the high-resolution phase. These include how long the high-resolution model must be run to correctly include a time history of material temperature. Another

issue is whether a high-resolution model optimized for daytime conditions is required for the night when radiant energy variation is considerably weaker. Also, it may prove desirable to allow the resolution of the high-resolution model to be variable so that detail is not over-specified for a low-spatial-resolution sensor.

#### Turbulent flux at varying spatial detail

38. In addition to the radiant terms, turbulent fluxes must be considered in the energy budgets for the low- and high-resolution phases of the 3-D temperature model. Initial values will be available as low spatial resolution from the MMM. Whether or not these values are adequate for the low-resolution calculation must be determined from experimentation. If spatial enhancement is necessary, an interface between the two scales will be developed. In any case, some adaptation of the MMM output will be necessary for high resolution and portions of the low-resolution energy budget. As stated above, a full CFD solution will be considered, but it is likely that some other simpler techniques akin to those used in the existing terrain surface temperature models (Balick et al. 1981) will be used.

#### Illumination and Scattering Models for Active Systems

39. The geometry and the ray-tracing/radiosity techniques in the high-resolution model will be utilized for simulating other spectral bands and sensor types. Sensors detecting scattered energy, such as active MMW and passive V/NIR, require additional specific illumination models (the 3-D atmospheric model could be used to illuminate the scene for V/NIR simulations). Also, the appropriate directional scattering functions for the spectral band will be paired with the ray-tracing or radiosity algorithms.

#### Directional Radiance Model

##### Temperature to radiance conversion

40. Techniques for modeling or specifying directional temperature to radiances conversion are required. Experimental evidence indicates that the emissivity of some surface types varies as a function of viewer angle, so the ability to include this effect should be part of the radiance calculation. Current capabilities in this regard seem primitive and spotty. Since many directional effects are strong, especially in the daytime, this is a priority

issue. Models of directional effects for different spectral regions will be investigated, acquired, or developed. In addition, a means to incorporate expert knowledge must be available where modeling results are considered inadequate.

41. The task of converting temperature to directional radiance, or calculation of reflected energy from active sensors, should be done in a way which will be useful for all sensor systems types. Facilitated methods to specify directional functions and scalars for materials in a generic manner are needed. A library of some (5 to 10) canonical directional distributions will be developed (isotropic emitter, strong retroemitter, etc). These distributions should also be useful for V/NIR and MMW reflection simulations.

#### Texture simulation

42. Texture will be required where detail is too great to allow individual element modeling (forest canopy, grass) or where the final scene resolution does not warrant a high level of spatial modeling. Texture generation or specification development is a priority since the state of the art seems primitive and quasi-empirical. Issues are the same as those for any other approach except that texture will be required only for the high-resolution model. Conceptually, texture can be included in the directional radiance or scattering phase of the system and may be related to high- or low-resolution model calculations for statistics such as means and variance.

### Scene Projection Process

#### Procedures and techniques

43. Once appropriate signatures are computed for all landscape features and surfaces in a defined geometrical area, projection of the final radiance "image" at the entrance plane of the sensor can be a relatively straightforward process, given the hardware features of today's graphics workstations. A thermal image consists almost entirely of energy directly emitted from surfaces, so possibly a z-buffer algorithm with selective ray tracing will be appropriate for the near term. Features such as shadows and corner reflections will be implicit in the surface energy budget calculation which makes use of ray tracing and radiosity calculations for the thermal modeling process. However, during the actual projection process, some fine details may be calculated which will require the selective ray-tracing approach.



#### Atmospheric effects on final sensor-plane radiance

44. Atmospheric effects can be added at this stage using Lowtran (Kneizys et al. 1983) or another appropriate model, since the sensor-to-pixel distance will be computed as part of the scene projection process. For sensors that view above the horizon, an atmospheric model will be used straightforwardly to simulate cloud-free sky radiance in the direction of the sensor. The viewing of clouds by the sensor is a complex issue which will be addressed later in the study. Effort will be put into utilizing the 3-D atmosphere simulated with the MMM to increase the accuracy of the propagation effects.

#### Validation, System-level Integration, and Sensitivity Analysis

45. Methods and opportunities to test, compare, and validate algorithms need to be established early in the program. Therefore, an algorithm testbed will be specified using scenarios established for a variety of sensor systems designs. The tasks defined above can be developed parallel with each other to some degree. Thus, as capabilities are developed, the testbed can be used to integrate the individual elements into an overall modeling package. This will allow testing of algorithms and enable a systems approach to selecting alternatives. Eventually, the system will need to be validated on a variety of well-documented test cases. Current graphics workstations are very appropriate for use in this task since they incorporate hardware to perform many necessary functions at high speed. In addition, they are supported by a great degree of commercial and public domain software for stand-alone applications, as well as concurrent operation with computers such as the CRAY.

46. Such a complicated set of models and other software described here must be integrated into an overall system to be useful. A systems-level approach will be taken to integrate individual algorithms and determine the sensitivity of the desired outputs to variations in the input data. A sensitivity analysis is necessary on preliminary versions of the testbed to examine the response of the overall model. The system must be tested and validated as a whole so that complex interactions of the individual algorithms will be observed. In this way the sensitivity analysis will provide feedback to allow updating and/or simplification of the algorithms after the effects of such trade-offs on accuracy are known.

#### PART IV: SUMMARY

47. A conceptual plan for developing a 3-D landscape signature modeling system has been described. The technology considered is, in many cases, at the leading edge of research in computer graphics and signature modeling. Modifications to elements of the plan will most likely be necessary when and if more effective alternatives become obvious as work progresses in these areas.

48. To get the program under way, experts in various fields, particularly in mesoscale meteorological modeling and radiosity/ray tracing, should be involved in the effort. Their knowledge will accelerate the pace of work and allow better utilization of leading-edge developments in the technical fields discussed in this paper. Again, acquisition of an appropriate, dedicated test platform is needed to begin testing concepts and approaches. The plan outlined here is considered to be realizable, but one should keep in mind that specific details are subject to modification as the program progresses and improved methods are found to better perform some of the major components of the plan. Major milestones have been developed for a program to implement the plan described here. These milestones are listed in Table 1, where time lines are relative to an FY93 starting date.

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Table 1  
Major Milestones for a Program Starting In FY93

Description	Estimated Time Line				
	FY93	94	95	96	97
Information Base Design and Development					
Object geometry and mesh generation	<-----	-----	-----	----->	
Visible, thermal, and MMW attributes		<-----	-----	----->	
Geometry database compression or enhancement procedure to match scale level of thermal model	<-----	-----	----->		
Texture library and procedures		<-----	-----	----->	
Preprocessor Models					
Mesoscale meteorological model	<-----	-----	----->		
3-D atmosphere radiance model and database linkages	<-----	-----	----->		
Thermal Modeling					
Component conduction models for objects that make up the scene	<-----	-----	-----	----->	
Low-resolution energy budget					
Radiosity and ray-tracing procedures for radiant energy exchange. Simple and complex (grass, canopy) surfaces	<-----	-----	----->		
Micro adjustments to MMM turbulent flux calculations		<-----	-----	----->	

(Continued)

Table 1 (Concluded)

Description	Estimated Time Line				
	FY93	94	95	96	97
High-resolution model					
Low-resolution to High-resolution interface for initial conditions	<-----	----->			
Geometry refinement and surface sampling procedure		<-----	----->		
High-resolution ray-tracing and radiosity calculations for total surface irradiance			<-----	----->	
Adaptive mesh refinement for shadow boundaries		<-----	----->		
Illumination and Scattering Models					
Bidirectional reflection functions and directional emittance models		<-----	----->		
MMW illumination and scattering models	<-----	-----	-----	-----	>
Directional Radiance					
Directional temperature to radiance calculation		<-----	----->		
Atmospheric propagation, obscurant			<-----	----->	
Scene Projection					
Procedure (hardware & software based)	<-----	-----	-----	-----	>
Specific sensor models. Imaging visible, thermal. Nonimaging radar. Hooks for incorporating new sensor models				<-----	----->

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